USAELRDL Technical Report 2310

TRANSIENT AND STEADY-STATE NUCLEAR RADIATION EFFECTS ON GERMANIUM PNP ALLOY TRANSISTORS

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UNITED STATES ARMY
ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
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U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
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ABSTRACT

Procedures and results of nuclear irradiations made on germanium alloy transistors are reported. The facilities used were the Penn. State University Reactor and the Sandia Pulsed Reactor. Transient results of I_{CBO} changes indicate dependence on applied voltage, with a resultant effective shunt resistance of 200 K. Changes in gain and in minority carrier lifetime were used to compute damage constants from data taken at both facilities. A factor of three is observed between the constants. Leakage current measurements and gain measurements are reported as functions of f_α.

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INTRODUCTION

Many groups of experimenters and theoreticians have, during the past several years, contributed much data and many theories concerning the effects of nuclear radiation on semiconductor devices, such as transistors or diodes. At first, most of these contributions concerned nuclear radiation in general, with no regard for the rate of delivery of the radiation to the devices under consideration. As time passed and more was learned about mechanisms of radiation damage, two separate types of studies began to develop; namely, exposures of devices to relatively low rate sources for lengthy periods of time, and exposures to very brief bursts of radiation with very high peak rates. The former types of studies were conducted, and still are being conducted, to observe at a leisurely pace what happens to create the so-called permanent damage effects. The latter variety of work being carried out is an effort to simulate what one might expect in the way of nuclear radiation from the detonation of a nuclear or thermonuclear type weapon.

Studies of this kind have resulted in a fair library of data and ideas. It has been our purpose during the past twelve months to plan experiments and acquire data to enable comparison of the effects observed on a given variety of transistorswhen exposed to the nuclear radiation environment extant in a power reactor (in this case the Pennsylvania State University 200 Kw facility) and to that found near a pulsed reactor (in this case the Sandia Pulsed Reactor Facility (SPRF)).

EXPERIMENTAL PROCEDURE

The Pennsylvania State University Reactor Experiments

The reactor facility available at Penn. State is of the swimming pool variety, capable of operation at a maximum power level of 200 Kw. At this level of operation, a target located underwater, and immediately adjacent to the reactor core, will be bombarded by a neutron flux of 2×10^{12} $N_f v$ (neutrons/cm^2-sec) with energies between 0.1 Mev and 10 Mev. In this report, N_f will refer to neutrons with energy > 0.1 Mev. The total dose received can be obtained either by calculating it from the power level of the reactor and the time of exposure, or by using some selected threshold detector and the measured spectrum of the reactor. In our experiments, the former system was employed with an occasional check being made with sulfur threshold dosimeters.

The actual experimental arrangements used in the two experiments at Penn. State discussed in this report, if examined carefully, will show a great improvement from the first to the second. In general, the system consists of a waterproof container, which houses the items under test, placed near the reactor core; a plastic tube containing the electrical connections from the submerged housing; the test circuitry, and a means of recording the information. In the first of these two experiments, the underwater container proved extremely awkward in that it was oriented horizontally and, being buoyant, quite difficult to lower on the instrument bridge. The plastic tubing used was heavy wall polyethylene, which became cracked during transit and tended to allow water to penetrate the system. These items did their job, but the system designed for the second experiment was much more efficient. For example, the container was oriented vertically and weighted with lead poured into the bottom. There was no problem whatever in lowering this tank to the bottom of the reactor pool. Also, the tubing used was lighter weight Tygon rather than polyethylene. Tygon will withstand the bending and rolling encountered in the laboratory and in transit.

The test circuits were basically the same in the two experiments; except that in the second one all devices not in the actual test circuit were switched to a common standby circuit which maintained d.c. bias on all such devices. During the first experiment, the devices were removed from the test circuit and left with no bias. In both experiments, the data was fed to a digital voltmeter with printout and recorded on printed tape. The devices under test were Ge alloy units arranged in a common base configuration, and the forward current transfer ratio α, was monitored consecutively on all devices. Upon completion of a set of α measurements, the emitter of the device under test was opened, and the collector-base leakage current I_{CBO} was monitored. Before and after measurements were also made on the effective minority carrier lifetime by the current injection technique described by Lederhandler and Giacoletto.[1] The nature of the data taken may be seen in Figure 1 showing α vs. Φ_f for the extremes of f_α, the cutoff frequency, under investigation, and in Figure 2, which shows the variation in I_{CBO} with Φ_f, again for the extremes in f_α.

The Sandia Pulsed Reactor Facility

The Sandia reactor is a bare critical assembly providing a mixed neutron and gamma pulse of about 50 microseconds width at half maximum. At the screen, which is as near to the core as it is possible to locate, a target will be exposed to approximately 10^{13} Nfvt (neutrons/cm^2) with energies greater than 0.1 Mev, and about 2500 rads (H_2O) from gamma rays. The neutron doses are measured by threshold dosimeters, mainly sulfur ($E > 2.9$ Mev), with an occasional set of fission foils to keep a check on the spectrum. The gamma ray dose is measured by the Bausch & Lomb glass microdosimeter system. All of this dosimetry is provided by The Sandia Corporation. A more complete description of the Facility may be found in a Sandia Corp. monograph.[2]

The circuitry and recording equipment were set up in a trailer outside of the reactor building with the components being tested mounted on a small chassis next to the reactor screen and connected to the trailer with approximately 150' lengths of RG-58 cable. Since the reactor pulse is very short, it is required to have a recording "channel" for each piece of information desired, and, as a result, the four oscilloscope traces can be utilized to record only three pieces of parametric data and one trace from a MgORAD to provide the pulse shape. For this reason, a much smaller quantity of data is available from the Sandia experiments than from Penn. State; however, some of this data is on the transient effects, about which there is currently great interest.

The devices under test were again germanium alloy units arranged in a common base configuration. In some of the tests, I_{CBO} was monitored with data being taken with different applied V_{CB}. In other tests, the output current, I_C, was monitored; however, circuit problems resulted in some rather unenlightening information in this area. The information was fed into oscilloscopes (Tektronix 555) and the resulting traces were photographed during the reactor burst. The transient I_{CBO} data is the most interesting transient information obtained in these experiments, and a plot of the peak change in I_{CBO} vs. the applied V_{CB} is shown in Figure 3. If one examines this data carefully and notes that the original values of I_{CBO} are much smaller than the transient values, a judicious application of Ohm's law reveals that there is a shunt resistance of approximately 200 K being dropped across the collector-base junction during the reactor burst. Pending closer study of other experimenters' data, it appears that this may possibly be an indicator that we are observing air ionization between leads <u>inside</u> the can, since 200 K is approximately the resistance of ionized air near the screen of the SPRF.

In an effort to compare SPRF produced effects with Penn. State produced effects, a set of transistors was placed on a plank which was laid radially outward from the reactor and left there for 16 pulses. In this manner a large dose was obtained, but with a much higher rate than at Penn. State. On these devices h_{FE} and τ_e were measured for permanent change.

RESULTS

The combined results of these previously described experiments can be presented in various forms. One form that is used rather prevalently is the relationship between $\Delta\alpha$ and Φ_f. Figure 4 shows data obtained from all of the experiments, broken into three separate categories according to f_α of the devices. From these curves, it can be seen that there is greater damage, represented by greater changes in α, at higher dose levels, and at lower values of f_α. This is understandable when one considers the relation derived in the literature:[3]

$$f_\alpha = \frac{1.22}{\pi}\left(\frac{D_p}{W^2}\right) \qquad (1)$$

where D_p is the diffusion constant for holes in the base of a pnp device and W is the base width. If f_α is high, then W must be narrower, thereby providing less volume in which lattice displacements can affect the passage of minority carriers, and, at the frequencies in question, the reduction in the minority carrier lifetime is the major cause of electrical degradation, manifested in the lowering of α.

Now, let us consider the damage constants involved in these experiments. According to Webster[4]

$$\frac{1}{\beta} = \frac{SWA_s}{D_pA_e} + \frac{\sigma_b W}{\sigma_e L_{ne}} + \frac{W^2}{2L_{pb}^2} \tag{2}$$

where: β = common emitter forward current transfer ratio

σ = conductivity

A_e = area of the emitter junction

A_s = effective surface recombination area around emitter

L = diffusion length

W = base width

S = surface recombination velocity.

From equation (1) and the fact that

$$L_{pb}^2 = D_p \tau_p \tag{3}$$

we arrive at the equation:

$$\frac{W^2}{2L_{pb}^2} = \frac{1.22}{2\pi}\left(\frac{1}{f_\alpha}\right)\left(\frac{1}{\tau_p}\right) \tag{4}$$

which can be substituted into equation (2) to give:

$$\frac{1}{\beta} = \frac{SWA_s}{D_pA_e} + \frac{\sigma_b W}{\sigma_e L_{ne}} + \frac{1.22}{2\pi f_\alpha}\left(\frac{1}{\tau_p}\right). \tag{5}$$

Now, according to Loferski,[5] the surface recombination term and the emitter efficiency term are unchanging with radiation, at least relative to the bulk term, at the frequencies of interest. Therefore, we can examine the difference between Webster's equation before irradiation and after irradiation:

$$\frac{1}{\beta_f} - \frac{1}{\beta_i} = \frac{1.22}{2\pi f_\alpha}\left(\frac{1}{\tau_{pf}} - \frac{1}{\tau_{pi}}\right) \tag{6}$$

where the subscript i indicates initial conditions, and the subscript f indicates conditions after irradiation.

Relating τ_{pf} to τ_{pi} by the following:[6]

$$\frac{1}{\tau_{pf}} = \frac{1}{\tau_{pi}} + \frac{\Phi_f}{K} \tag{7}$$

where Φ_f = total integrated neutron dose in neutrons/cm^2, with energy greater than 0.1 Mev

and K = the damage constant.

Combining equations (6) and (7),

$$\frac{1}{\beta_f} - \frac{1}{\beta_i} = \frac{1.22}{2\pi f_\alpha}\left(\frac{\Phi_f}{K}\right). \tag{8}$$

Lifetime changes are available on only some of the devices; however, on these, it is of interest to compare the values of K calculated directly from equation (7), which values will be referred to as K_τ, and those calculated from equation (8), which values will be referred to as K_β. If the ratio, r_K, of $\frac{K_\beta}{K_\tau}$ is computed for each of the fifteen devices exposed at Sandia on which both lifetime and gain changes were recorded, and the results averaged, a value of r_K is obtained of 3.2 ± 1.7. On six devices exposed at Penn. State, the computed ratio is 1.7 ± 0.5. The constant that is generally referred to as the damage constant is K_τ. Reference 6 gives a K for n-type Ge of $5.0 \pm 2.0 \times 10^7$ Nvt-sec. The fact that the above difference exists between K_τ and K_β may be explained by the fact that the injected carrier transport mechanism is not solely diffusion.

Some experimenters have indicated possible differences in amount of damage for the same radiation dose administered in different spectral distributions.[7] This problem arises because the dose is given in terms of all neutrons having E > some value which is not the damage threshold. Data taken during these experiments yield the following values of K_β averaged over the number of devices shown:

Penn. State Expt. #1	8 Units	$(1.05 \pm 0.19) \times 10^8$	Nvt-sec.
Penn. State Expt. #2	20 Units	$(2.1 \pm 0.8) \times 10^8$	Nvt-sec.
Sandia Expt. #1	20 Units	$(5.2 \pm 2.2) \times 10^7$	Nvt-sec.
Sandia Expt. #2	66 Units	$(3.5 \pm 1.3) \times 10^7$	Nvt-sec.

It is readily apparent that there is a significant difference in the K_β's obtained in the two different environments. The two values obtained in one environment may be averaged, as can the other two, and then a ratio, r_{Env}, can be obtained. The data above yield a value of $r_{Env} = 3.6 \pm 2.5$ by statistical error treatment. This factor is attributed to the different dose rates of the two environments used. If one expressed the dose in terms of all neutrons with energy greater than 400 e.v., the factor would be even larger due to the spectral differences in the two environments.

The values of K calculated so far have been made on the basis of an actual constant existing. No further calculations will be made, but it may be of interest to note that, as shown in Figure 5, the values of K_τ as calculated from Sandia data have somewhat of a dependence on the total neutron flux. Figure 6, showing data on K_τ taken at two different total exposures at Penn. State show an opposite dependence on total dose. An attempt to explain the significance of these observations will not be made at this time.

CONCLUSIONS

The conclusions reached are applicable to the particular family of devices on which these data were collected, i.e., germanium alloy, PNP devices with a range of f_α from 3.3 mc. to 13.2 mc. The conclusions are as follows:

1. Permanent gain degradation is inversely proportional to f_α.

2. Permanent increase in I_{CBO} is directly proportional to f_α.

3. Transient increases in I_{CBO} are directly proportional to the applied voltage, V_{CB}, indicating a shunt resistance of 200 K.

4. The damage constants calculated from changes in minority carrier lifetimes are approximately one-third the value of the constants calculated from changes in β. This indicates that in the units under study, the injected carrier transport mechanism is not solely diffusion.

5. The damage constants obtained on devices exposed at Penn. State were about three times as large as those obtained on devices exposed at Sandia. This indicates that three times as much permanent damage was done by the high-rate pulsed radiation received at Sandia as was done by the same dose of low-rate radiation received at Penn. State. If the total dose is expressed as all neutrons having energy greater than 400 ev., rather than 100 Kev., this factor would be still larger, since the PSU spectrum is richer in low energy neutrons than is the SPRF spectrum.

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The authors wish to note contributions made in the planning and conducting of these experiments by Sp/4 Gary D. Thomas and PFC William C. Bush. The personnel of the Sandia Corp. and of the Pennsylvania State University Reactor Facility also contributed by their cooperation in the

use of their facilities. Some of the original suggestions leading to this set of experiments were made by Mr. Frederick Gordon, Jr., Deputy Chief, S & M Branch.

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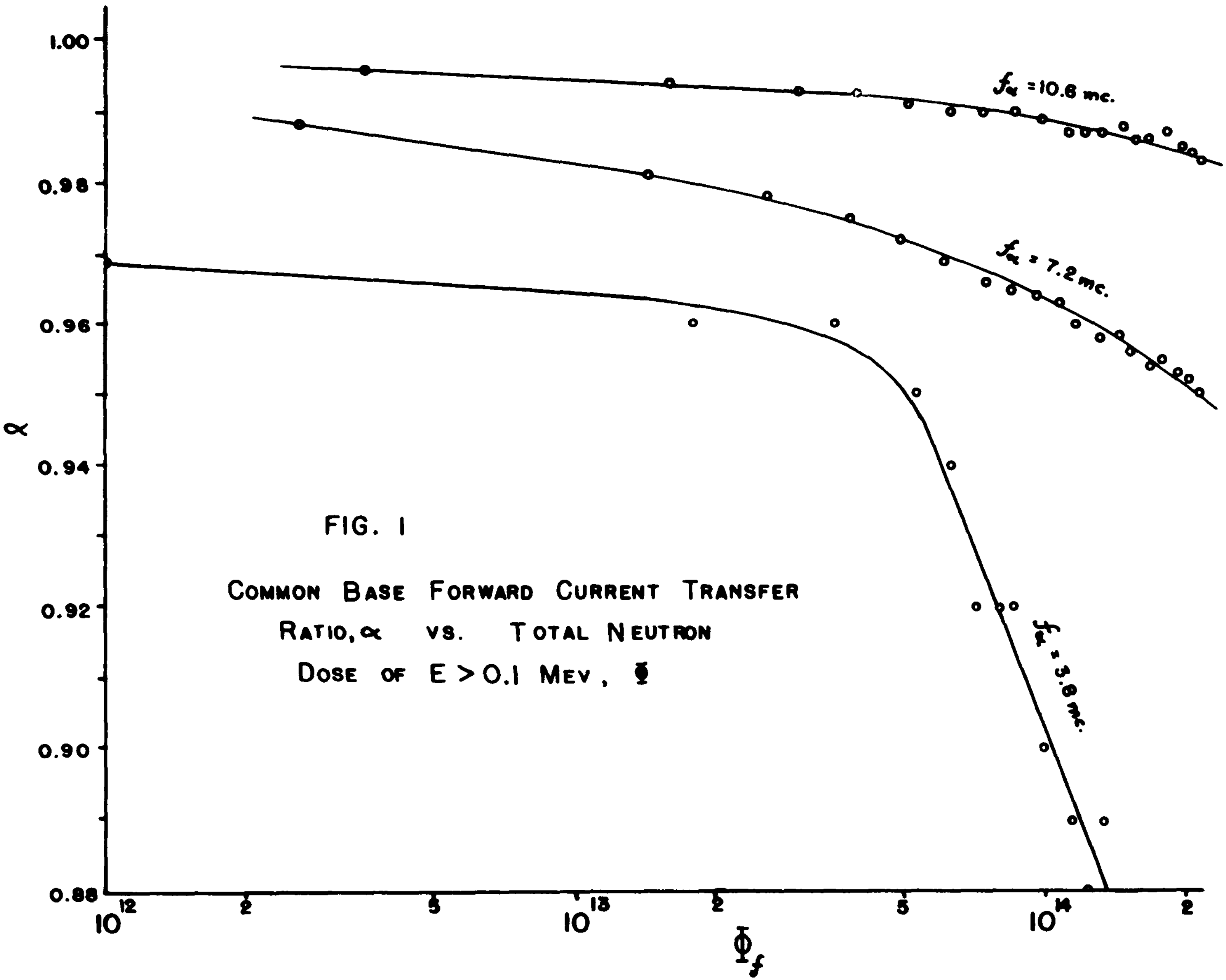


FIG. 1

COMMON BASE FORWARD CURRENT TRANSFER RATIO, α VS. TOTAL NEUTRON DOSE OF E > 0.1 MEV, Φ

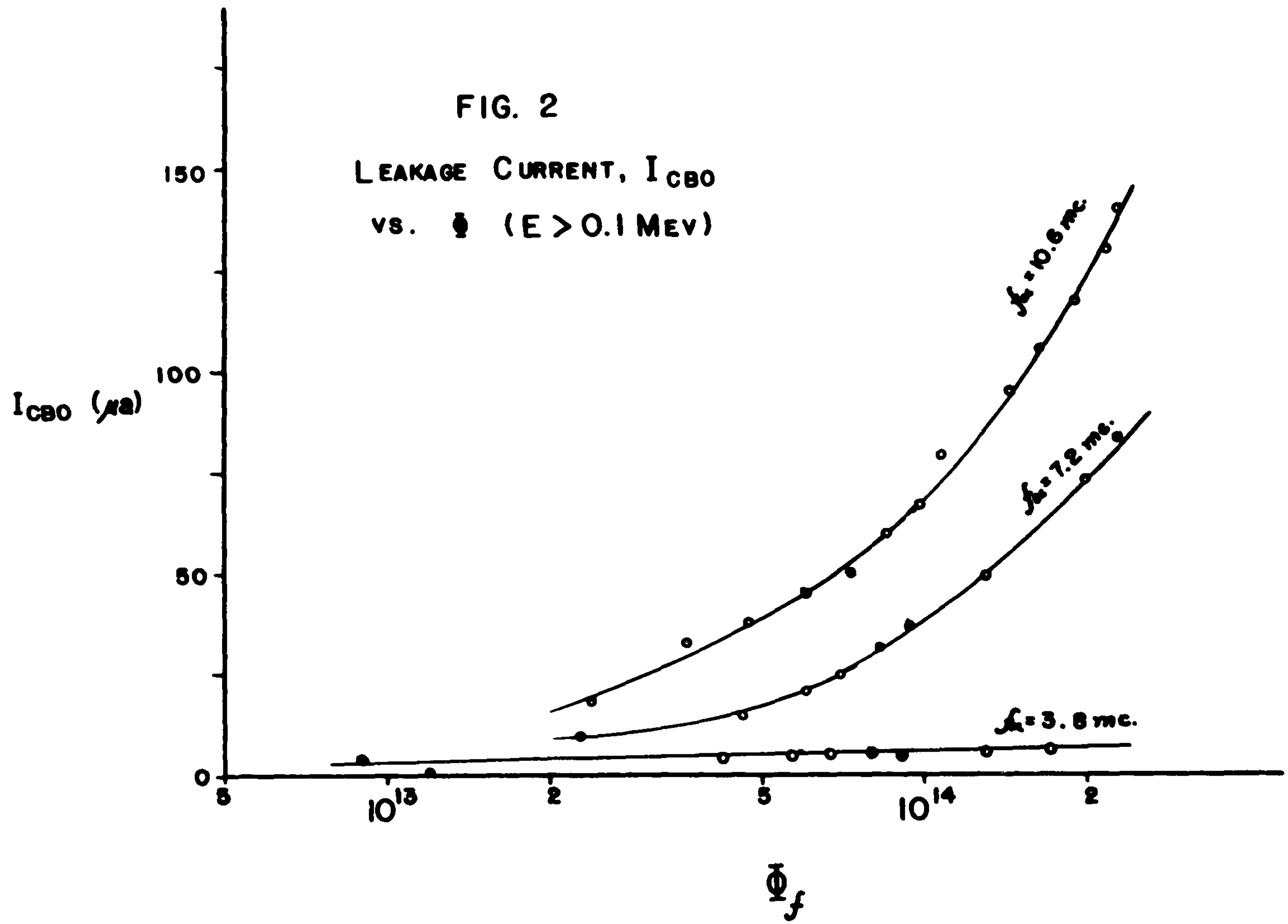


FIG. 2

LEAKAGE CURRENT, I_{CBO} vs. Φ (E > 0.1 MEV)

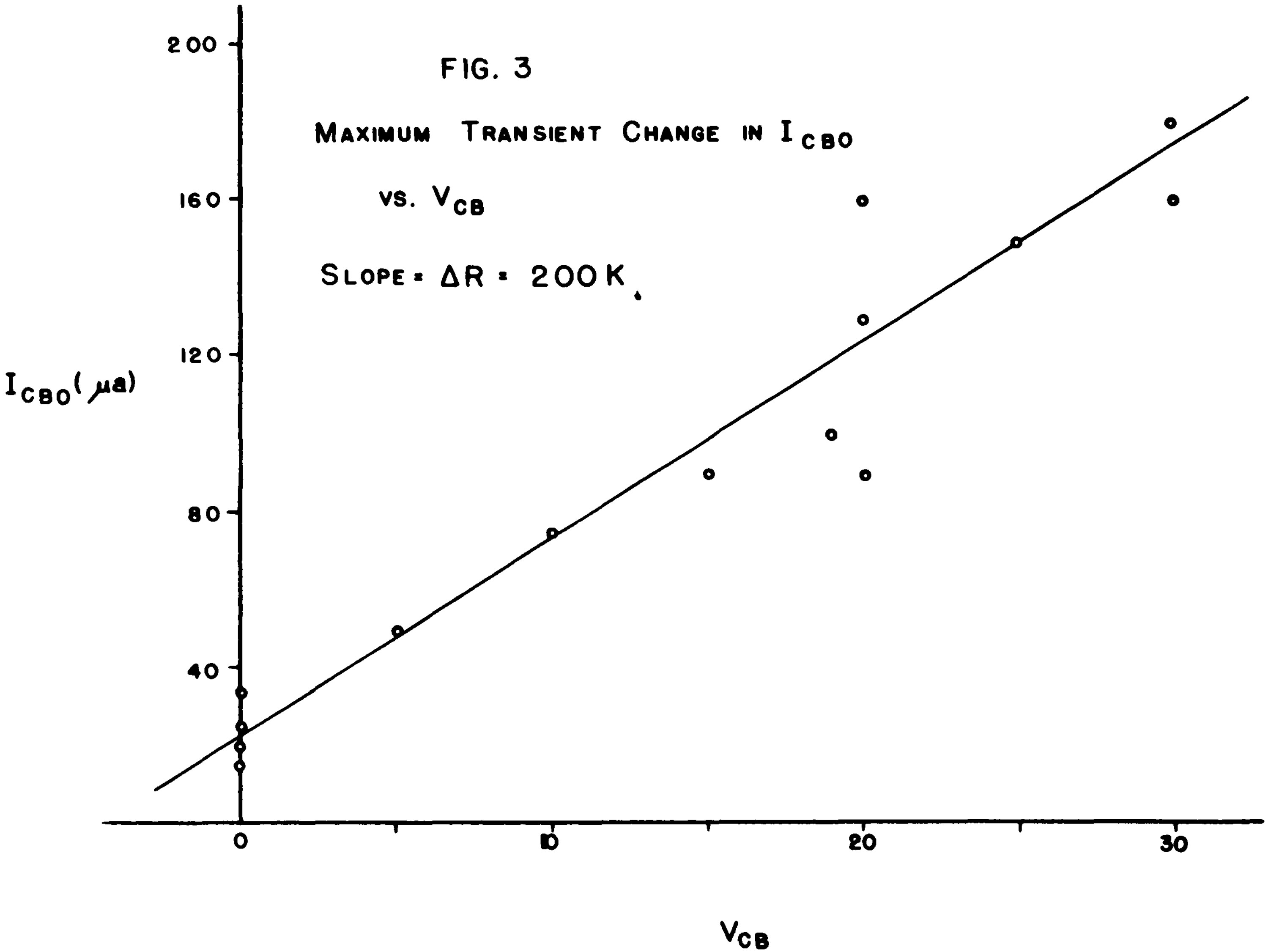


FIG. 3

MAXIMUM TRANSIENT CHANGE IN I_{CBO}

VS. V_{CB}

SLOPE = ΔR = 200K.

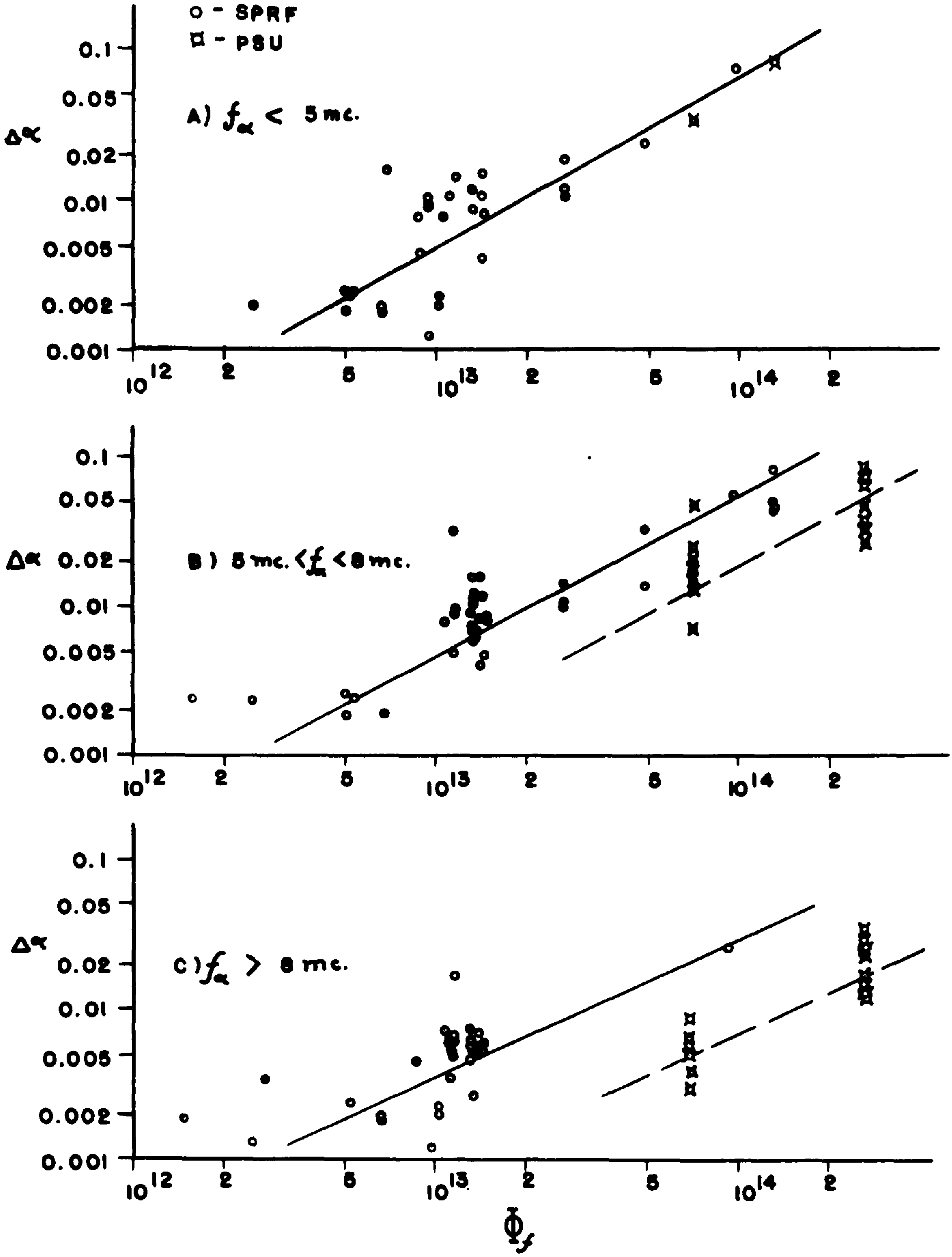
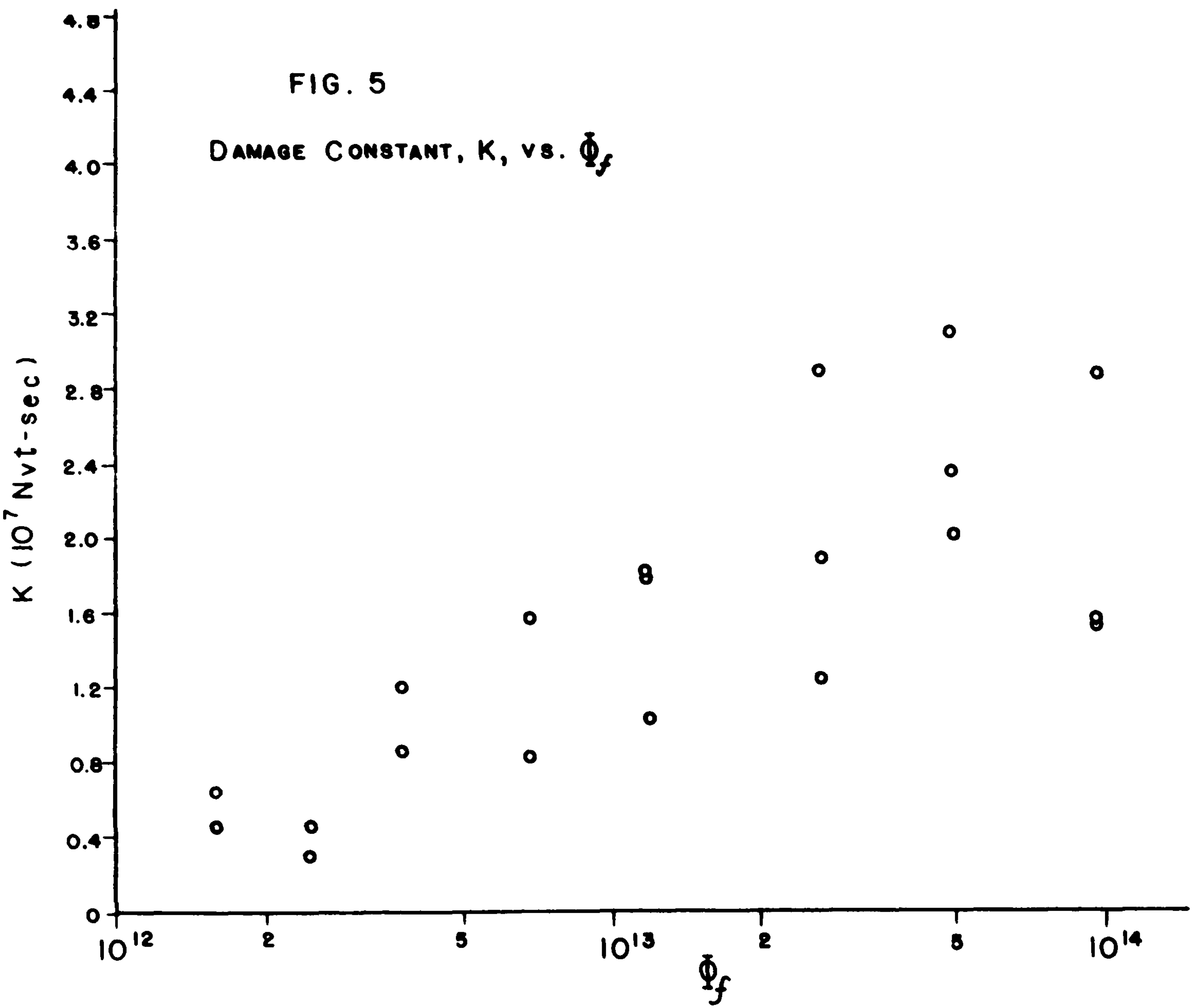


FIG. 4. DEGRADATION IN α VS. Φ_f

FIG. 5

DAMAGE CONSTANT, K, VS. Φ_f



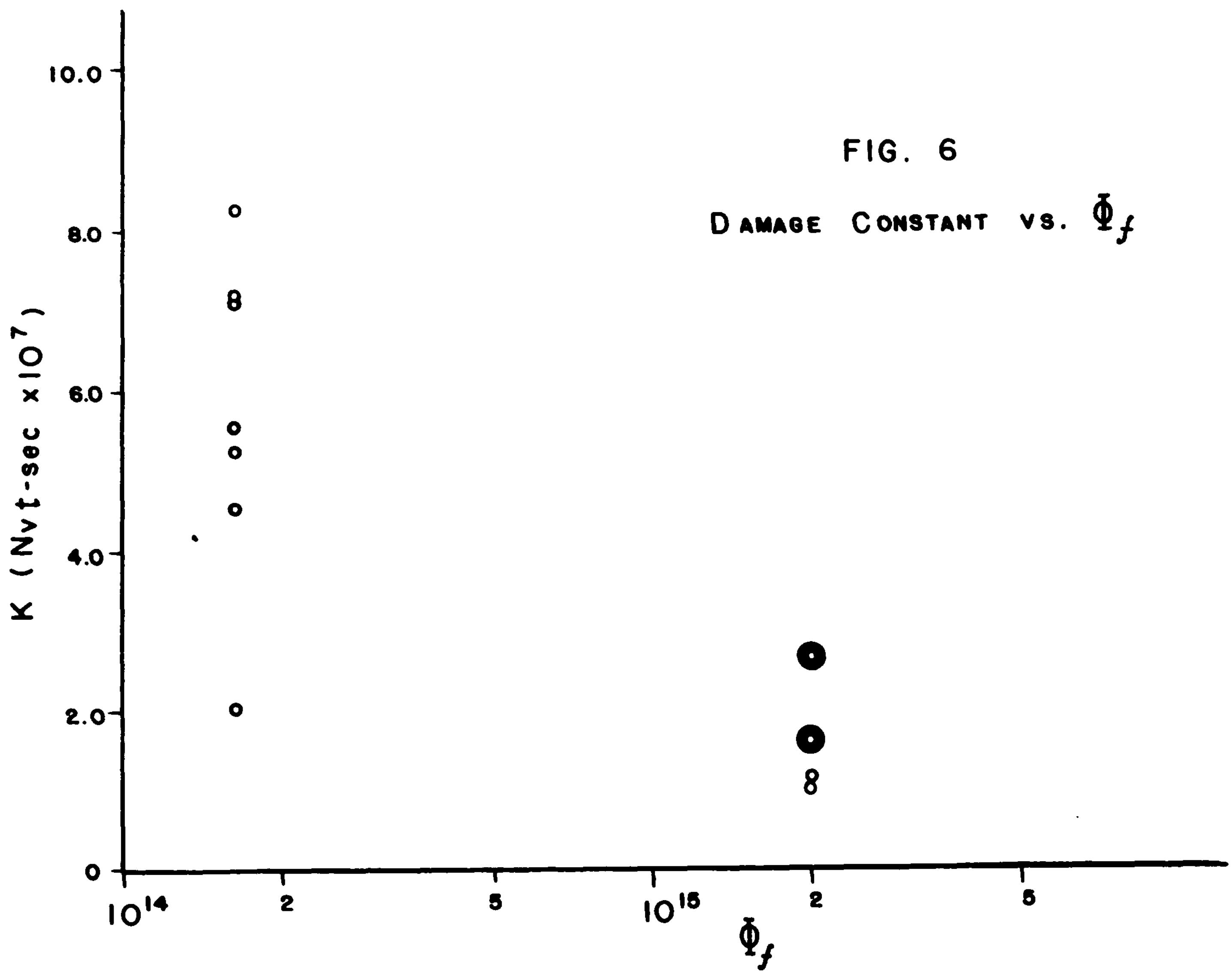


FIG. 6

DAMAGE CONSTANT vs. Φ_f

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Procedures and results of nuclear irradiations made on germanium alloy transistors are reported. The facilities used were the Pennsylvania State University Reactor and the Sandia Pulsed Reactor. Transient results of I_{CBO} changes indicate dependence on applied voltage, with a resultant effective shunt resistance of 200 K. Changes in gain and in minority carrier lifetime were used to compute damage constants from data taken at both facilities. A factor of three is observed between the constants. Leakage current measurements and gain measurements are reported as functions of f_α.

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2. Transistors

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